INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY
AT PRINCETON UNIVERSITY, 1989-1990

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SUMMARY OF RESEARCH

The Air Transportation Technology Program at Princeton University, a program emphasizing graduate and undergraduate student research, proceeded along six avenues during the past year:

- Microburst Hazards to Aircraft
- Machine-Intelligent, Fault-Tolerant Flight Control
- Computer-Aided Heuristics for Piloted Flight
- Stochastic Robustness of Flight Control Systems
- Neural Networks for Flight Control
- Computer-Aided Control System Design

This research has resulted in a number of publications, including theses, archival papers, and conference papers. An annotated bibliography of publications that appeared between January, 1989, and June, 1990, appears at the end of this report. The research that these papers describe was supported in whole or in part by the Joint University Program, including work that was completed prior to the reporting period.

Severe downdrafts and resulting high velocity outflows caused by microbursts present a significant hazard to aircraft on takeoff and final approach. *Microbursts*, which are often associated with thunderstorm activity, also can occur in the vicinity of dissipating convective clouds that produce no rainfall at ground level. Microburst encounter is a rare but extremely dangerous phenomenon that accounts for one or two air carrier accidents and numerous general aviation accidents each year (on average). Conditions are such that an aircraft's performance envelope may be inadequate for safe penetration unless optimal control strategies are known and applied.

Our current wind shear research focuses on avoiding wind shear during transport aircraft operations, as well as on developing a cockpit simulation of wind shear encounter. Graduate student Alex Stratton is developing an expert system for wind shear avoidance that extends the FAA Microburst Windshear Guidelines to account for temporal and spatial variations in the evidence that wind shear is present [1]. The approach being taken is to develop a Bayesian Belief Network that relates information gathered from many sources to determine the probability of encountering a microburst on the intended flight path. Our principal objectives are to develop methods for assessing the likelihood of wind shear encounter (based on real-time information in the cockpit), for deciding what flight path to pursue (e.g., abort, go-around, normal climbout, or glide slope), and for using the aircraft's full potential to combat wind shear. This study requires the definition of deterministic and statistical techniques for fusing internal and external information, for making "go/no-go" decisions, and for generating commands to the aircraft's autopilot and flight directors in automatic and manually controlled flight.

Graduate student Sandeep Mulgund has begun the development of a fixed-base cockpit simulator for microburst studies. The simulation incorporates a cockpit station with manual input devices and a graphical display of instruments and the "out-the-window" view. Currently the simulator is programmed to simulate a twin-jet transport aircraft and a single-engine general aviation airplane. Displays for the "out-the-window" view and the control panel devices are generated entirely by computers and are presented on color cathode-ray tubes. The external view is generated and displayed by a Silicon Graphics IRIS 3020 Workstation. A central computing unit performs dynamic and control calculations, accepts analog inputs, drives the panel displays, and commands the external view. It is a special-purpose Multibus computer employing parallel 80286 processors and special-purpose graphics boards, which are controlled by an IBM PC-AT computer.

Undetected system failures and/or inadequately defined recovery procedures have contributed to numerous air carrier incidents and accidents. The infamous DC-10 accident at Chicago's O'Hare Airport, in which loss of an engine pod, subsequent loss of subsystems, and asymmetric wing stall led to disaster, provides a prototype for the kind of tragedy that could be averted by intelligent flight control systems. (An intelligent control system is one that uses artificial intelligence concepts, e.g., an expert systems program, to improve performance and failure tolerance.) Although many methods of modern control theory are applicable, the scope of the problem is such that none of the existing theories provides a

complete and practical solution to the problem. At the same time, heuristic logic may be applicable, but it has yet to be stated in satisfactory format.

Graduate student David Handelman developed a knowledge-based reconfigurable flight control system that could be considered a prototype for a failure-tolerant control system constructed with available hardware. The knowledge-based flight control system is specified initially and tested using the LISP programming language. When desired logic is determined, the corresponding Pascal code is generated automatically for real-time implementation (which has been demonstrated in a laboratory environment) [2,3]. Chien Huang addressed the failure-analysis problem in his Ph.D. thesis [4], and he developed a method for online control reconfiguration based on proportional-integral implicit model-following [5]. Parvadha Suntharalingam examined three alternatives for model-following control in her M.S.E. thesis [6].

Helping a pilot make quick decisions under high workload conditions is important for aircraft missions of all types. In research principally supported by an Army/Navy grant but reported at numerous quarterly reviews of the Joint University Program, Brenda Belkin has developed an expert system of expert systems called AUTOCREW. In her M.S.E. thesis [7], Ms. Belkin uses the paradigm of a hypothetical aircraft crew to facilitate the assignment of tasks, rules, and data within parallel knowledge bases. AUTOCREW performs a cyclical search in which the Director expert system, the electronic analog of the aircraft commander, establishes goals that invoke the crew-member expert systems. The crew members then perform such tasks as observation, monitoring, and control in response to continuing needs as well as special requests from the Director. Particular attention was paid to the navigation expert system, which manages diverse sensor inputs under varied trajectory and failure scenarios [8].

Control system robustness is defined as the ability to maintain satisfactory stability or performance characteristics in the presence of all conceivable system parameter variations. While assured robustness may be viewed as an alternative to gain adaptation or scheduling to accommodate known parameter variations, more often it is seen as protection against uncertainties in plant specification. Consequently, a statistical description of control system robustness is consistent with what may be known about the structure and parameters of the plant's dynamic model. Guaranteeing robustness has long been a design objective of control system analysis, although in most instances, insensitivity to parameter variations has been treated as a deterministic problem. Graduate students Laura Ryan Ray and Chris Marrison are investigating a simple numerical procedure for estimat-

ing the *stochastic robustness* of control systems. Monte Carlo evaluation of the system's eigenvalues allows the *probability of instability* and the related *stochastic root locus* to be estimated. This analysis approach treats not only Gaussian parameter uncertainties but non-Gaussian cases, including uncertain-but-bounded variations [9-13,14,15]. Trivial extensions of the procedure admit alternate discriminants to be considered. Thus, the probabilities that stipulated degrees of instability will be exceeded or that closed-loop roots will leave desirable regions also can be estimated. Results are particularly amenable to graphical presentation.

There is growing interest in the use of neural networks for computational decision-making and control, brought about by the advent of small, fast, inexpensive computers. The neural network paradigm offers a potentially attractive structure for flight control systems that adapt to changing flight conditions and system failures, but much is to be learned about the practicality of such an approach. Graduate student Dennis Linse has begun to examine this potential. Current research focuses on the use of two types of neural networks (feed-forward back-propagation network and cerebellar model articulation controller) in an adaptive nonlinear controller based upon feedback linearization [16,17]. In this application, a suite of six neural networks represents the nonlinear aerodynamic/thrust model of the aircraft, and the model can be trained both before and during operational flight.

Graduate student Subrata Sircar has begun to examine concepts for the next generation of computer-aided control system design. The principal goal is to add knowledge-based features to the design logic, such as background autonomous anticipatory operation, which will keep the computer busy performing useful work while the user is evaluating the next course of action, and new graphical output paradigms. The control designer should be able to enter the control equations directly, with as few restrictions and special conventions as possible. The approach will use the Control Equation Parser (CEP), previously developed at Princeton, which accepts symbolic expressions and performs the needed translations using the LISP programming language. The present embodiment of CEP has three parts (preprocessor, parser, and postprocessor), and it runs on both the Symbolics 3670 LISP Machine and the NeXT Computer.

ANNOTATED REFERENCES OF 1989-90 PUBLICATIONS

1. R. Stengel and D.A. Stratton, An Expert System for Wind Shear Avoidance, *Engineering Applications of Artificial Intelligence*, Vol. 2, No. 3, Sept 1989, pp. 190-197. (also *Proceedings of the 1989 American Control Conference*, Pittsburgh, June 1989, pp. 349-354.)[*]

A study of intelligent guidance and control concepts for protecting against the adverse effects of wind shear during aircraft takeoffs and landings is being conducted, with current emphasis on developing an expert system for wind shear avoidance. Principal objectives are to develop methods for assessing the likelihood of wind shear encounter (based on real-time information in the cockpit), for deciding what flight path to pursue (e.g., takeoff abort, landing go-around, or normal climbout or glide slope), and for using the aircraft's full potential for combating wind shear. This study requires the definition of both deterministic and statistical techniques for fusing internal and external information, for making "go/no-go"decisions, and for generating commands to the aircraft's autopilot and flight directors for both automatic and manually controlled flight. The program has begun with the development of the Wind Shear Safety Advisor, an expert system for pilot aiding that is based on the FAA Wind Shear Training Aid, a two-volume manual that presents an overview, pilot guide, training program, and substantiating data that provides guidelines for this initial development. The Wind Shear Safety Advisor expert system currently contains over 200 rules and is coded in the LISP programming language.

2. D. Handelman and R. Stengel, Combining Expert System and Analytical Redundancy Concepts for Fault-Tolerant Flight Control, *J. Guidance, Control, and Dynamics*, Vol. 12, No. 1, Jan-Feb 1989, pp. 39-45.[*]

A technique for rule-based fault-tolerant control is presented. The objective is to define methods for designing control systems capable of accommodating a wide range of aircraft failures, including sensor, control, and structural failures. A software architecture that integrates quantitative analytical redundancy techniques and heuristic expert system concepts for the purpose of in-flight, real-time fault tolerance is described. The resultant controller uses a rule-based expert system approach to transform the

Archival Papers[*]
Conference Papers[**]
Ph.D. Theses[+]
M.S.E. Theses[++]

problem of failure accommodation task scheduling and selection into a problem of search. Control system performance under sensor and control failures using linear discrete-time simulations of a tandem-rotor helicopter's dynamics is demonstrated. It is found that the rule-based control technique enhances existing redundancy management systems, providing smooth integration of symbolic and numeric computation, a search-based decision-making mechanism, straightforward system organization and debugging, an incremental growth capability, and inherent parallelism for computational speed.

3. Handelman, D.A., *A Rule-Based Paradigm for Intelligent Adaptive Flight Control*, Ph. D. Thesis, Princeton University, Report No. 1858-T, April 1989.[+]

Although fault tolerance always has been an important aspect of aircraft design, the reduced static stability and increased maneuverability of modern aircraft complicate the problem by shortening the amount of time available to detect, identify, and adjust for component failures. This dissertation investigates the use of highly integrated symbolic and numeric processing in real-time knowledge-based systems for enhanced automatic aircraft failure accommodation. A rule-based control technique is proposed whereby procedural activity is attained through the manipulation of declarative expressions. Rules are used to encode common-sense dependencies, to incorporate expert knowledge on specific situations, and to invoke algorithmic mathematical procedures. Task execution occurs as a by-product of search through these knowledge-base rules. Also proposed is a rule-based controller development system that utilizes a high-level symbolic LISP environment for preliminary system design. Automatic LISP-to-Pascal knowledge-base translation is used to provide dramatically increased execution speed and an environment for highly integrated symbolic and numeric computation. The utility of the control technique is demonstrated through the construction of a multi-processor Rule-Based Flight Control System (RBFCS) for a CH-47 tandem-rotor helicopter. The RBFCS is shown to accommodate multiple simulated failures affecting the electrical, hydraulic, and stability augmentation subsystems of the helicopter. It is concluded that declarative rules with embedded procedural code provide a sound basis for the construction of complex control systems.

4. C. Huang, *A Methodology for Knowledge-Based Restructurable Control to Accommodate System Failures*, Ph. D. Thesis, Princeton University, Report No. 1869-T, Aug 1989.[+]

The problem of dealing with unanticipated failures of dynamic systems is addressed. The solution centers on developing a knowledge-based approach to perform online failure isolation and system reconfiguration. The failure analysis employs inference mechanisms and causal relationships among the devices to generate probable failure models, which are pruned and ranked by the use of heuristic measures. Hypotheses for other probable causes are made if the failure model does not adequately account for the anomalies. After the failure source is identified, the system knowledge base is updated and the impact of failure is assessed. Any degradation of system performance caused by failures is restored by restructuring the control. This issue is studied in depth and addressed by the analysis and design of an implicit-model-following control law. The concepts and methodologies of the approach are illustrated via many examples and further substantiated using a number of failure scenarios involving a tandem-rotor helicopter. The results show that by providing a form of intelligent self-organization, the knowledge-based restructurable control approach potentially is capable of accommodating unanticipated failures.

5. C. Huang and R. Stengel, Restructurable Control Using Proportional-Integral Implicit Model Following, *J. Guidance, Control, and Dynamics*, Vol. 13, No. 2, Mar-Apr 1990, pp. 303-309.[*]

Studies of a proportional-integral implicit-model-following control law are presented. The research focuses on the ability of the control law to recover the performance of a system with failed actuators or structural damage to its prefailure level. Properties of the implicit-model-following strategy are examined, and conditions for control reconfiguration are stated. The control law is applied to the lateral-directional model of a fighter aircraft, and control restructuring is shown for changes in control and system matrices. It is concluded that the implicit-model-following scheme is a good candidate for control reconfiguration.

6. P. Suntharalingam, *Applications of Computer-Aided Control System Design to Linear Quadratic Model-Following*, M.S.E. Thesis, Princeton University, Report No. MAE-1868-T, Aug 1989.[++]

This thesis deals with the application of optimal control methods to aircraft flight dynamics. The technique of model-following control has been found to be an effective way of incorporating certain design specifications into the formulation of a linear-quadratic control law. This project focused, in particular, on the behavior of the implicit model-follower and the explicit model-follower. The design criterion for the former controller is the minimization of the difference between plant and model dynamics, and the latter controller is based on minimization of the error between plant and model states. In addition, in an attempt to combine the favorable aspects of both methods, a hybrid model-follower was developed, incorporating features of both implicit and explicit model-followers.

The relative performance of the three controllers was evaluated by examining eigenvalues, time responses, robustness, and reconfiguration possibilities following failure. Results indicate that the explicit model-follower is superior in aspects of robustness and steady-state performance. The implicit model-follower offers specific advantages in the transient response to command input and in the use of lower gains. The hybrid controller combined desirable aspects of the two controllers, yielding the best overall performance.

7. Belkin, B.L., *Cooperative Rule-Based Systems for Aircraft Navigation and Control*, M.S.E. Thesis, Princeton University, Report No. MAE-1856-T, June 1989.[++]

This thesis proposes a design methodology for the development of multiple cooperating rule-based systems for aircraft. Nine systems, collectively called AUTOCREW, were designed to automate functions and decisions. The organization of tasks is described, details of knowledge-base development and implementation are given, and performance metrics for evaluating the workload of each knowledge base are demonstrated. Several test scenarios were evaluated using an interactive graphical simulation on an IBM PC-AT computer. Software tools developed to aid in high-level design also are described. Results show that these tools facilitate rapid prototyping of a complex system exhibiting knowledge-base cooperation, satisfactory logic flow, and human pilot-AUTOCREW interaction.

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Design of one of the component expert systems, the Navigation Sensor Management (NSM) module, was pursued in considerable detail. This problem was chosen because it presented the challenge of designing an expert system from simulation data, that is, from quantitative test results. The NSM Expert was systematically derived from Kalman filter covariance data for simulated missions flown with seven different navigation system types. This development used Analysis of Variance (ANOVA) and the "ID3" algorithm. The function of the NSM Expert was to determine optimal navigation strategies from a set of available sensors based on a root-sum-square metric. Results show that the NSM Expert predicted position accuracy between 65 and 100 percent of the time for a specified "navaid" configuration and aircraft trajectory; hence, this decision-making logic could be incorporated in a scheme for best navaid selection. The systematic nature of the ANOVA/ID3 method makes it broadly applicable to expert system design when experimental or simulation data are available.

8. B. Belkin and R. Stengel, Quantitative Knowledge Acquisition for Expert Systems, presented at the *Space Operations, Applications, and Research Symposium*, Albuquerque, NM, June 1990.**

A common problem in the design of expert systems is the definition of rules from empirical data obtained in system operation or simulation. While it is relatively easy to collect numerical data and to log the comments of human operators engaged in experiments, generalizing such information to a set of rules has not previously been a straightforward task. This paper presents a statistical method for generating the needed rule base from numerical data, motivated by an example based on vehicle navigation with multiple sensors. The specific objective is to design an expert system that selects a satisfactory suite of measurements from a dissimilar, redundant set, given an arbitrary navigation geometry and possible sensor failures.

This paper describes the systematic development of a Navigation Sensor Management (NSM) Expert System from Kalman Filter covariance data. The development method consists of the two statistical techniques: *Analysis of Variance (ANOVA)* and the *ID3 algorithm*. The ANOVA technique indicates whether variation of a problem parameter gives *statistically* different covariance results, and the ID3 algorithm identifies the *relationships* between the problem parameters using probabilistic knowledge extracted from a simulation example set. ANOVA results show that statistically different position accuracies are obtained when different navaids are used, the number of navigation aids is changed, the trajectory is varied, or the performance history is altered. By indicating that these four

factors significantly affect the decision metric, an appropriate parameter framework was designed, and a simulation example base was created. The example base contained over 900 training examples from nearly 300 simulations. The ID3 algorithm was used to determine the NSM Expert's classification "rules" in the form of *decision trees*. The performance of these decision trees was assessed on two arbitrary trajectories, and the performance results are presented using a predictive metric. The test trajectories used to evaluate the system's performance show that the NSM Expert adapts to new situations and provides reasonable estimates of the expected hybrid performance. The results also show how the NSM Expert chooses optimal or next-best navigation strategies when limited computational resources are available; in simple cases, its solutions are commensurate with the designer's intuition.

9. R. Stengel and L. Ryan, Stochastic Robustness of Linear Control Systems, *Proceedings of the 1989 Conference on Information Sciences and Systems*, The Johns Hopkins University, Baltimore, Mar 1989, pp. 556-561.**

A simple numerical procedure for estimating the *stochastic robustness* of a linear, time-invariant system is described. Monte Carlo evaluation of the system's eigenvalues allows the *probability of instability* and the related *stochastic root locus* to be estimated. This definition of robustness is an alternative to existing deterministic definitions that addresses both structured and unstructured parameter variations directly. This analysis approach treats not only Gaussian parameter uncertainties but non-Gaussian cases, including uncertain-but-bounded variations. Trivial extensions of the procedure admit alternate discriminants to be considered. Thus, the probabilities that stipulated degrees of instability will be exceeded or that closed-loop roots will leave desirable regions also can be estimated. Results are particularly amenable to graphical presentation.

10. R. Stengel and L. Ryan, Stochastic Robustness, oral presentation at the SIAM Conference on Control in the 90's, San Francisco, May 1989.**

This paper is an extension of the above paper with extended numerical results for the Doyle LQG counterexample. In particular, the comparison of stochastic robustness with singular-value analysis is pursued; whereas the latter provides only qualitative guidelines for "loop transfer recovery," the former provides a specific solution for the amount of robustness recovery required as a function of parameter uncertainty.

11. R. Stengel and L. Ryan, Multivariate Histograms for Analysis of Linear Control Systems, *Proceedings of the 1989 American Control Conference*, Pittsburgh, June 1989, pp. 937-943.**

A simple numerical procedure for estimating the *stochastic robustness* of a linear, time-invariant system is described. Based on Monte Carlo evaluation of the system's eigenvalues, this analysis approach introduces the *probability of instability* as a scalar measure of stability robustness. The related *stochastic root locus*, a portrayal of the root probability density, provides insight into robustness characteristics. Parameter variations are not limited to Gaussian parameter uncertainties; non-Gaussian cases, including uncertain-but-bounded variations, can be considered as well. Confidence intervals for the scalar probability of instability address computational issues inherent in Monte Carlo simulation. An example demonstrates stochastic robustness as applied to an aircraft control system in which parameters are alternately considered to have Gaussian, uniform, or binary probability distributions.

12. R. Stengel and L. Ryan, Application of Stochastic Robustness to Aircraft Control, *Proceedings of the 1989 AIAA Guidance, Navigation & Control Conference*, Boston, Aug 1989, pp. 698-708.**

Stochastic robustness, a simple numerical procedure for estimating the stability robustness of linear, time-invariant systems, is applied to a forward-swept-wing aircraft control system. Based on Monte Carlo evaluation of the system's closed-loop eigenvalues, this analysis approach introduces the *probability of instability* as a scalar stability robustness measure. The related *stochastic root locus* provides insight into robustness characteristics of the closed-loop system. Three linear-quadratic controllers of increasing robustness are chosen to demonstrate the use of stochastic robustness to analyze and compare control designs. Examples are presented illustrating the use of stochastic robustness analysis to address the effects of actuator dynamics and unmodeled dynamics on the stability robustness of the forward-swept-wing aircraft.

13. R. Stengel, Stochastic and Deterministic Analysis of Nonlinear Flight Control Systems, oral presentation at the *NASA Ames-UC Berkeley Nonlinear Flight Control Workshop*, Berkeley, Aug 1989.**

The flight dynamic equations for aircraft motion are inherently nonlinear, yet linear analysis has played a large role in the design and analysis of flight control systems. The principal reason is that the pilot has been

able to provide the underlying nonlinear trim control manually, and perturbations from the trim condition often are small. When large-amplitude perturbations from trim are important, nonlinear effects need to be considered. Deterministic models provide the basis for all analysis of aircraft motions. They are used directly to examine stability and response and indirectly to form the underpinnings of stochastic models. Stochastic effects fall into two distinct categories: uncertain response brought about by random inputs and initial conditions, and uncertain response arising from parametric uncertainty.

After briefly reviewing the nature of aircraft dynamics, a progression through four topics is made: *locally linearized control laws, adaptive nonlinear-inverse-dynamic (NID) control, analysis of control saturation effects, and stochastic robustness of closed-loop controllers*. Experiences with multi-input/multi-output linearized models are recounted, leading to validation of a linear-quadratic-Gaussian (LQG) pilot model by ground-based simulation and of a gain-scheduled LQG digital controller by helicopter flight test. Feedback linearization has been applied to the design of an all-axis controller for a general-aviation airplane, providing inherent protection against stalls and spins, as well as satisfactory flying qualities over the aircraft's entire flight envelope. This NID controller was shown to operate in real time using multiple microprocessors, and a mechanism for adapting it to the aerodynamic characteristics of individual aircraft was developed. Phase-plane analysis of the effects of control saturation on the closed-loop stability of open-loop-unstable aircraft is considered next, with stability boundaries defined by both open and closed regions of piecewise-linear-system trajectories. Finally, the topic of stochastic robustness is presented, based principally on results obtained for linear, time-invariant models of aircraft dynamics, with directions for application to nonlinear systems noted.

14. L. R. Ray and R. Stengel, Stochastic Stability and Performance Robustness of Linear Multivariable Systems, *Proceedings of the 1990 American Control Conference*, San Diego, May 1990.**

Stochastic robustness, a simple technique used to estimate the robustness of linear, time-invariant systems, is applied to a single-link robot arm control system. Concepts behind stochastic stability robustness are extended to systems with estimators and to stochastic performance robustness. Stochastic performance robustness measures based on classical

design specifications are introduced, and the relationship between stochastic robustness measures and control system design parameters is discussed. The application of stochastic performance robustness and the relationship between performance objectives and design parameters are demonstrated by means of an example. The results prove stochastic robustness to be a good overall robustness analysis method that can relate robustness characteristics to control system design parameters.

15. R. Stengel, Analysis of Stochastic Robustness in Linear Systems, oral presentation at the *Eighth Army Conference on Applied Mathematics and Computing*, Mathematical Sciences Institute, Cornell University, June 1990.**

This is an oral summary of material presented in earlier papers.

16. D. Linse and R. Stengel, System Identification for Nonlinear Control Using Neural Networks, *Proceedings of the 1990 Conference on Information Sciences and Systems*, Princeton University, Mar 1990.**

An approach to incorporating artificial neural networks in nonlinear, adaptive control systems is described. The controller contains three principal elements: a nonlinear-inverse-dynamic control law whose coefficients depend on a comprehensive model of the plant, a neural network that models system dynamics, and a state estimator whose outputs drive the control law and train the neural network. Attention is focused on the system-identification task, which combines an extended Kalman filter with generalized-spline function approximation (e.g., basis splines, back-propagation feedforward networks, or cerebellar model articulation controller networks). Continual learning is possible during normal operation (without taking the system off line for specialized training). Nonlinear-inverse-dynamic control requires smooth derivatives as well as function estimates, imposing stringent goals for the approximating technique.

17. D. Linse and R. Stengel, Neural Networks for Function Approximation in Nonlinear Control, *Proceedings of the 1990 American Control Conference*, San Diego, May 1990.**

Two neural-network architectures are compared with a classical spline interpolation technique for the approximation of functions useful in a nonlinear control system. A standard back-propagation feedforward neural

network and a cerebellar model articulation controller (CMAC) are presented, and their results are compared with a B-spline interpolation procedure that is updated using a recursive least-squares analysis. Each method is able to accurately represent a one-dimensional test function. Trade-offs between size requirements, speed of operation, and speed of learning indicate that neural networks may be practical for identification and adaptation in a nonlinear control environment.

ANNOTATED BIBLIOGRAPHY OF 1989-90 PUBLICATION

1. P. Shrivastava and R. Stengel, Stability Boundaries for Aircraft with Unstable Lateral-Directional Dynamics and Control Saturation, *J. Guidance, Control, and Dynamics*, Vol. 12, No. 1, Jan-Feb 1989, pp. 62-70.*

Aircraft that do not possess inherent stability must rely on closed-loop control systems for stable operation. Because there are limits on the deflections of an aircraft's control surfaces, the region of stable operation also is bounded. These boundaries are investigated for a lateral-directional example in which vertical fin size is inadequate to provide directional stability and where aileron and rudder deflections are subject to saturation. Fourth-order models are used for this study, with flight control logic based on minimum-control-energy linear-quadratic-regulator theory. It is found that the stability boundaries can be described by unstable limit cycles surrounding stable equilibrium points. Variations in regions of stability with gain levels and command inputs are illustrated. Current results suggest guidelines for permissible limits on the open-loop instability of an aircraft's lateral-directional modes.